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LETTER

Buoyless Nets Reduce Sea Turtle Bycatch in Coastal Net Fisheries

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Abstract

Coastal entangling net fisheries are globally ubiquitous and have substantial socioeconomic importance, especially in developing nations. Bycatch in coastal nets results in high mortality of vulnerable megafauna including seabirds, marine mammals, and sea turtles, and has led to fisheries closures that incur high social costs. The overlap of intense bottom-set net fisheries with a high-density foraging hot spot of endangered loggerhead turtles at Baja California Sur, Mexico (BCS) produces among the highest recorded megafauna bycatch rates worldwide. From 2007 to 2009, we conducted controlled experiments in partnership with local fishermen at BCS to compare turtle bycatch rates with target catch rates, composition, and market value between conventional (control) and buoyless (buoys removed from float line) nets. In 136 controlled sets of net pairs, buoyless nets reduced mean turtle bycatch rates by 68% while maintaining target catch rates and composition. Our results suggest that buoyless nets offer a promising approach for mitigating sea turtle and potentially other megafauna bycatch while maintaining coastal net fisheries worldwide.

Introduction

As human populations continue to expand, fishing effort is increasing in coastal areas worldwide (Stewart *et al.* 2010). Coastal small-scale fisheries employ more than 99% of the world's 51 million fishers and provide over half of the planet's wild-caught seafood products (Berkes *et al.* 2001; Chuenpagdee *et al.* 2006), underscoring their environmental and socioeconomic importance (Begossi 2006; Halpern *et al.* 2008). However, declining catches, inadequate resources and infrastructure, and overcapacity all highlight the challenges associated with managing small-scale fisheries (Sumaila *et al.* 2008; Madau *et al.* 2009; Stewart *et al.* 2010; Shester & Micheli 2011).

Entangling net fisheries are globally ubiquitous and have substantial socioeconomic and nutritional importance to coastal communities, especially in developing nations (FAO 2008). Nets have proliferated over the past 30 years because they are inexpensive and lucrative as well as easy to build, fish, and maintain. Notwithstanding, net fisheries have been identified as one of the leading sources of overfishing and bycatch worldwide (Chuenpagdee *et al.* 2003; FAO 2008). Their use in coastal small-scale fisheries has been linked to declines in commercially important fish populations (Sala *et al.* 2004), and their incidental capture (bycatch) can lead to high mortality in nontarget species and alter ecosystem structure and function (Shester & Micheli 2011). Bycatch in nets is particularly problematic for vulnerable air-breathing marine megafauna including sea turtles, marine mammals, sirenians, and seabirds (Lewison *et al.* 2004, 2014; Heppell *et al.* 2005; Zydelis *et al.* 2009), and has been known or believed to cause declines in a number of populations worldwide (D'Agrosa *et al.* 2000; Tasker *et al.* 2000; Read *et al.* 2006; Peckham *et al.* 2007b, 2008; Alfaro-Shigueto *et al.* 2011; Casale 2011; Crowder & Heppell 2011; Hamer *et al.* 2013; Wallace *et al.* 2013).

Recent research suggests that bycatch of megafauna in small-scale coastal net fisheries might approach or even exceed bycatch in some industrial fisheries (Jaramillo-Legorreta *et al.* 2007; Peckham *et al.* 2007a, 2008; Alfaro-Shigueto *et al.* 2011; López-Barrera *et al.* 2012; Mancini *et al.* 2012). However, unlike industrial-scale fisheries, small-scale fisheries often lack adequate resources and infrastructure to assess and regulate their bycatch impacts (Shester & Micheli 2011). In certain high-profile cases, governments have limited the use of nets in order to protect endangered megafauna populations including an international ban on the use of driftnets in the North Pacific (Wetherall *et al.* 1993), and restriction of net use in the Gulf of California to protect the vaquita porpoise (D'Agrosa *et al.* 2000). However, due to the great commercial and nutritional importance of coastal net fisheries, especially in developing nations, creative solutions that mitigate megafauna bycatch while maintaining fisheries are urgently needed.

Increased awareness of the importance of megafauna bycatch impacts over the past two decades (Dayton *et al.* 1995; Hall 1996; Lewison *et al.* 2004, 2014) has led to innovations in fishing gear and techniques that have resulted in reduced bycatch in a variety of fisheries (Hall *et al.* 2000; Gilman *et al.* 2005, 2006, 2009; Werner *et al.* 2006; Senko *et al.* 2014a). However, mitigating net bycatch has proven challenging because nets are inherently nonselective, and changing net characteristics such as mesh size and techniques such as soak time often result in substantial reductions in target catch (Gilman *et al.* 2009). Developing gear modifications for small-scale net fisheries is important because more selective fishing practices may be less profitable and flexible (i.e., the inherent nonselectivity of nets allows fishers to retain multiple target and sometimes nontarget species). Net modifications have previously resulted in megafauna bycatch mitigation in certain fisheries without substantial reductions in target catch. Seabird bycatch was reduced with the use of high-visibility net in a coastal salmon gillnet fishery in Washington, DC, USA (Melvin *et al.* 1999); porpoise bycatch was reduced in the New England gillnet fishery with the use of acoustic pingers (Kraus *et al.* 1997), and recent research suggests that sea turtle bycatch in bottom-set nets can be reduced at night through net illumination (Wang *et al.* 2010, 2013).

The overlap of intense bottom-set net fisheries with a highly productive foraging hot spot for loggerhead turtles (*Caretta caretta*) at Baja California Sur, Mexico (BCS) (Peckham *et al.* 2007b; Wingfield *et al.* 2011) produces among the highest recorded megafauna bycatch rates worldwide (Peckham *et al.* 2007b, 2008, 2013; INAPESCA 2012), primarily of large juveniles and subadults (Peckham *et al.* 2007b) of high demographic importance (Crouse *et al.* 1987; Crowder *et al.* 1994). The resulting mortality is of international concern because loggerhead turtles are globally endangered (IUCN 2013), and the North Pacific population was recently uplisted to endangered under the U.S. Endangered Species Act (NOAA 2011) and identified as one of the world's most endangered sea turtle populations (Wallace *et al.* 2011).

To address the loggerhead bycatch problem at BCS, we have partnered directly with BCS net fishers since 2004, convening workshops and running experimental trials to design, test, and implement bycatch mitigation measures as part of a long-term fisher-led community-based conservation program (Peckham & Maldonado-Diaz 2012). In 2007, at the recommendation of local master fishermen, we together began investigating the viability of buoyless nets. Informal fisher interviews suggested that buoyless nets could be lucrative and reduce turtle bycatch. Thus, we took the simple but counterintuitive step of removing the buoys from float lines of conventional nets. To assess the effects of this net modification, we conducted controlled in-situ experiments in partnership with local fishermen at BCS to compare turtle bycatch rates with target catch rates, composition, and market value between traditional (control) and buoyless (buoys removed from float line) nets. Our study is unique in that we quantified the effects of a gear modification simultaneously on both target catch and bycatch rates in operating coastal net fisheries, yielding a comprehensive evaluation of the viability of this novel bycatch mitigation strategy.

Methods

Field trials

From 2007 to 2009, we conducted in-situ controlled experiments at Puerto López Mateos, BCS (see map of study site in Peckham *et al.* 2007b) in local bottom-set net fisheries during the summer fishing seasons to examine the effects of buoyancy of the net float line on turtle bycatch rates and target fish catch rates, composition, and market value by pairing buoyless (buoys removed from float line) and conventional (control) nets. Buoyless nets were set adjacent to control nets (within 100 m) at approximately the same depths (15–56 m) within the loggerhead hot spot where high levels of turtle bycatch had previously been recorded (Peckham *et al.* 2007b).

The west coast of BCS represents one of Mexico's most productive fishing grounds. Among myriad fisheries, grouper (*Mycteroperca* sp.), halibut (*Paralichthys californicus*), guitar-fish (*Rhinobatus* sp.), and other valuable groundfish are targeted by local small-scale fleets using bottom-set nets. In northwestern Mexico (and most of the world), nets are built with a monofilament mesh tied between two lines: a sink line rigged with lead weights and a float line rigged with buoys. To ensure that our trials were commercially valid in terms of target catch, all fishing was directed and conducted by local fishermen. Fishers selected fishing locations to maximize their target catch, and we substituted buoyless nets for a subset of their conventional nets. Buoyless nets were matched with control nets of the same dimensions and mesh size to form experimental pairs. Individual nets ranged in mesh size from 20.3 to 25.4 cm, in length from 111.12 to 120.38 m, and in height from 3.5 to 5.5 m. Control nets contained roughly 1 buoy every 1.7 m along the float line, for a total of 70 buoys per net. Experimental (buoyless) nets contained roughly 1 buoy every 8.5 m of float line, or 15 per net. As such, the experimental nets are not completely without buoys on the float line, but they are called buoyless by fishermen because of their considerably reduced use.

In the summers of 2007 and 2008, we conducted 40 pairs of controlled opportunistic trials by substituting buoyless nets for a subset of participating fishermen's conventional nets. In exchange for fishing two buoyless-control net pairs and carrying an observer onboard, we compensated fishermen US $50 per day-trip, and the fishermen retained the catch. Nets were checked daily between 0700 and 1,000, resulting in soak times of 23–25 hours. In the summer of 2009, we conducted 96 pairs of controlled experimental trials by hiring partner fishermen to fish experimental net pairs exclusively. To avoid turtle mortality, nets were checked three times a day, between 0700–0900, 1,600–1,800, and 2,300–0100, resulting in total soak times of 21–23 hours. All sea turtles caught were tagged with Inconel metal tags, measured, and released. The tagging and morphometric data were incorporated in the Grupo Tortuguero long-term monitoring database.

Table 1 Target catch composition by price class in buoyless and control nets (species list grouped by price class showing *N*, % of catch during study, mean and SD of catch rate per trip, and 2009 market price)

	Control		Buoyless	
First class ($2.4–3.2)	*N*	%	*N*	%
Mycteroperca xenarcha, M. jordani	22	10.58	16	7.69
Epinephelus acanthistius	12	5.77	4	1.92
Mycteroperca prionura	1	0.48	4	1.92
Epinephelus niphobles	0	0.00	1	0.48
Epinephelus itajara	5	2.40	6	2.88
SUM	40	19.23	31	14.90
Second class ($1.6–2.4)				
Lutjanus peru	1	0.48	4	1.92
Paralichthys californicus	11	5.29	21	10.10
Atractoscion nobilis	22	10.58	19	9.13
Lutjanus argentiventris, L. colorado	41	19.71	30	14.42
SUM	75	36.06	74	35.58
Third class ($1.6–0.8)				
Sphyrna zygaena	2	0.96	0	0.00
Brotula clarkae	1	0.48	1	0.48
Seriola lalandi	2	0.96	3	1.44
Semicossyphus pulcher	4	1.92	3	1.44
Mustelus lunulatus, Mustelus californicus	1	0.48	2	0.96
Paralichthys californicus	3	1.44	14	6.73
Cynoscion parvipinnis	0	0.00	1	0.48
Caulolatilus princeps	1	0.48	0	0.00
SUM	14	6.73	24	11.54
Fourth class ($0.8–0.1)				
Raja binoculata, R. inornata	3	1.44	2	0.96
Gymnura marmorata	2	0.96	3	1.44
Myliobatis californicus	54	25.96	37	17.79
Balistes polylepis	1	0.48	0	0.00
Rhinobatus productus	13	6.25	32	15.38
Paralabrax clathratus	2	0.96	7	3.37
Rhinoptera steindachneri	2	0.96	0	0.00
Anisotremus interruptus	1	0.48	8	3.85
Diplectrum pacificum	1	0.48	7	3.37
SUM	79	37.98	96	46.15

Data analysis

The bycatch-per-unit effort (BPUE) for each net was determined as: BPUE = the number of turtles captured/(net length/100 m) $*$ (soak time of net/24 hours). The catch-per-unit effort (CPUE) for each net was determined as: CPUE = kg of target species of fish/(net length/100 m) $*$ (soak time of net/24 hours). Catch composition from each net was identified and categorized in partnership with host fishermen into four groups by market value per kg: group 1 (US$2.4–3.2), group 2 (US$ 1.6–2.4), group 3 (US$ 1.6–0.8), and group 4 (US$ 0.8–0). Market value of each species caught was determined by a market survey conducted by two master fishermen from Puerto López Mateos (each with over 20 years fishing experience) and converted from pesos to dollars (Table 1). Market value of each group per trip was calculated by multiplying the catch volume of each group by its market value. Market value of each trip was calculated by summing the market value of all four groups per trip. We used paired bootstrap resampling to test the null hypothesis that there would be no difference in BPUE, CPUE, and market value between buoyless and control nets. Data were resampled 10,000 times using SYSTAT 12.0. This approach measures the strength of evidence against a null hypothesis rather than showing significance at a certain probability level (Manly 2007).

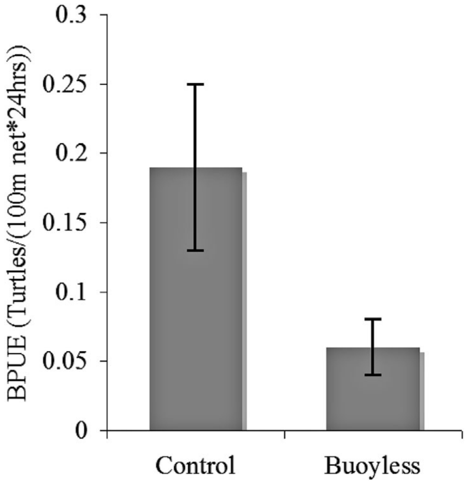

Figure 1 Comparison of sea turtle BPUE using buoyless versus control nets. Buoyless nets resulted in a 68% reduction in the mean BPUE from the control nets, and analysis with paired bootstrap resampling indicated that the BPUE was significantly lower ($n = 136$, $P = 0.002$). Bars represent SE.

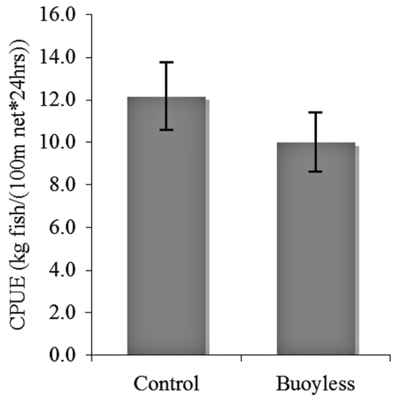

Figure 2 Comparison of target fish CPUE using buoyless versus control nets. Mean CPUE in buoyless nets was 18% lower than in control nets, but analysis with paired bootstrap resampling indicated that the CPUE was not significantly different between net treatments ($n = 136$, $P = 0.092$). Bars represent SE.

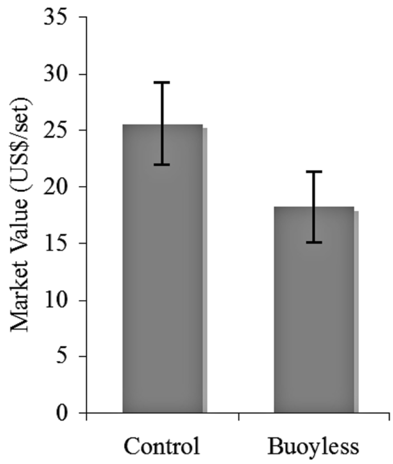

Figure 3 Comparison of market value per paired set in buoyless versus control nets. The mean value of catch using buoyless nets was 29% lower than the catch value of control nets and analysis with paired bootstrap resampling indicated that market value was significantly lower ($n = 136$, $P = 0.009$). Bars represent SE.

Results

In 136 controlled sets of net pairs, 36 sea turtles were caught: 32 loggerheads, 3 green turtles (*Chelonia mydas*), and 1 olive ridley (*Lepidochelys olivacea*). Turtle BPUE rates were significantly lower in buoyless nets (0.06 ± 0.3 turtles 100 m net^{-1} 24 hour^{-1}; mean ± SE) than in control nets (0.19 ± 0.7; Figure 1; $N = 136$, $P = 0.002$), with a 68% reduction in mean turtle bycatch rates and 67% fewer turtles caught in buoyless nets (9 turtles) than in control nets (27 turtles).

Catch of target fish was similar between the two net deigns with 1,456.6 and 1,801.2 kg of fish landed in buoyless and control nets, respectively. Mean CPUE was 18% lower in buoyless (9.9 ± 1.4 kg 100 m net^{-1} 24 hour^{-1}) than in control nets (12.0 ± 1.6; Figure 2), but the overall difference was not significant ($N = 136$, $P = 0.081$). Catch composition by species remained consistent between both net treatments (Table 1). Total market value of target fish caught was 29% lower in buoyless ($2,481) than in control nets ($3,477). Market value was significantly lower in buoyless ($18±3) than in control nets ($25 ± 4; $N = 136$; $P = 0.009$; Figure 3), with a 28% reduction in mean value compared to control nets.

Discussion

The selectivity of fishing nets can be increased by identifying and exploiting differences in the habitat use or perception capabilities of target versus nontarget species (Gilman *et al.* 2009). Reducing the vertical profile of nets has been shown to lower sea turtle bycatch (Price & Van Salisbury 2007), while illuminating nets has been found to reduce catch rates of sea turtles at night (Wang *et al.* 2010, 2013). Our results suggest that removing the buoys from net float lines can reduce turtle bycatch while maintaining target catch rates and composition, representing a bycatch mitigation solution with strong potential for commercial adoption.

Although buoyless nets yielded levels of catch volume similar to that of conventional nets, the market value of the catch of buoyless nets was marginally but significantly lower, an important factor for uptake by local fishers. However, this divergence likely resulted from unusually high landings of high-value yellow snapper

(*Lutianus Argentiventris*) by one crew in August 2009, in which 70 individuals of this species were caught during 2 weeks of buoyless net trials. No other individuals were caught in 2009, and in 2007 and 2008 combined, only one was captured by all crews.

Due to the deep working depth of our host fleet and poor underwater visibility, we have not been able to observe how buoyless nets work relative to conventional nets. The float lines our partners used on their nets consisted of 8 mm nylon (universally used in the BCS region), so they have inherent buoyancy that we surmise keeps the nets partially open and elevated in the water column (as opposed to lying flat on the seafloor). We suspect that the buoyless float lines hang lower in the water column than those of conventional nets. As a result, it is likely that the vertical profile of the buoyless nets is reduced. This probably decreased sea turtle encounter rates as in other studies in which net profile was reduced (Price & Van Salisbury 2007). Despite the lower profile of buoyless nets, similarity in target catch may result from increased fish entanglement probability as a result of the slack net, similar in function to the enhanced catch of nets equipped with tie-downs (Gilman *et al.* 2009). If turtles visually locate nets to forage out of them, it is also possible that removing the buoys removed a visual cue used to locate nets. We recommend future research with underwater cameras mounted on nets to better understand how buoyless nets function and interact with target and nontarget species in relation to conventional nets.

There are minimal costs involved in adopting buoyless nets instead of conventional nets at BCS and elsewhere. Conventional nets can be converted by simply removing the buoys from the float line, requiring roughly 1–2 hours work per net. Building new buoyless nets is less expensive than building conventional nets because the cost of buoys is saved (roughly 20% of total net cost). Furthermore, no training is required for fishermen to adopt buoyless gear because they are fished identically to conventional nets. One caveat is that some fishers report increased net tangling on certain substrates, specifically high relief ledge habitats.

Although buoyless nets present low cost of adoption and are comparable in profitability to conventional nets under normal oceanographic conditions, there may be social barriers to adoption of the gear among fishermen. Their function is counterintuitive for fishermen who have spent decades designing and building nets to enhance fish encounter rates by maximizing net surface area. Despite some skepticism at the outset of our study, by the end of the trials more than 80% of the 20 participating fishermen reported that they would permanently switch to buoyless nets (E. Caballero-Aspe, unpublished data). The potential for uptake of the buoyless gear was probably enhanced by our participatory research program, an approach that has been documented to be effective in a variety of other studies (Jenkins 2007, 2010; Campbell & Cornwell 2008). We worked to both educate and empower local fishermen through a combination of outreach events, workshops, and leadership roles through which they developed and tested potential bycatch reduction solutions (Peckham & Maldonado-Diaz 2012).

Despite the promise of buoyless nets for reducing sea turtle bycatch, we are not recommending their adoption by the fleets that primarily impact loggerhead turtles at BCS. Given the endangered status of the North Pacific loggerhead population (NOAA 2011), its distinction as one of the world's most vulnerable sea turtle populations (Wallace *et al.* 2011), and their extraordinarily high mortality in local net fleets (Peckham *et al.* 2007b, 2008; INAPESCA 2012), conservation action that effectively eliminates their bycatch is urgently needed. For example, in a parallel study, local fishermen have demonstrated the profitability of replacing nets with hook and line gear of zero turtle bycatch (H. Peckham, unpublished data), and local fishers have also expressed interest in fish traps that would substantially reduce turtle bycatch. In addition to the increased selectivity of these fishing practices (Shester & Micheli 2011), fishers can generate greater profits by gaining access into premium markets by catching higher quality fish in better condition. Finally, given the inherent difficulties associated with promoting and enforcing adoption of buoyless nets, we conclude that promoting hook and line and/or trap fishing is the better strategy in this extreme case.

Although we are not recommending their adoption by local net fleets at the Baja California Sur loggerhead hot spot, buoyless nets could represent a comprehensive or partial solution for reducing turtle bycatch in other regions of the world where net fisheries overlap with less depleted sea turtle populations. For instance, bycatch of green turtles in some coastal areas (e.g., López-Barrera *et al.* 2012; Mancini *et al.* 2012; Senko *et al.* 2014b) could be mitigated with the use of buoyless nets. Because the buoyless design likely exhibits decreased vertical net profile, they may also result in lower bycatch of other vulnerable air-breathing megafauna including seabirds, cetaceans, pinnipeds, and sirenians. Site and species-specific testing is necessary to establish their utility in other fisheries and regions.

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